THE APPLICABILITY OF X-RAY DIFFRACTION METHODS OF STRESS MEASUREMENT TO NAVAL STRUCTURES WITH AN INVESTIGATION OF THE STRESS DISTRIBUTION IN A STIFFENED PLATE

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March 17,
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Cambridge, Massachusetts,
May 18, 1949.

Professor J. S. Newell,
Secretary of the Faculty,
Massachusetts Institute of Technology,
Cambridge, Massachusetts.

Dear Professor Newell:

In accordance with the requirements for the degree of "Naval Engineer," we submit herewith a thesis entitled "The Applicability of X-ray Diffraction Methods of Stress Measurement to Naval Structures with an Investigation of the Stress Distribution in a Stiffened Plate."

Respectfully,

THE APPLICABILITY OF X-RAY DIFFRACTION METHODS OF STRESS MEASUREMENT TO NAVAL STRUCTURES WITH AN INVESTIGATION OF THE STRESS DISTRIBUTION IN A STIFFENED PLATE

by

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SYMBOLS

d	interatomic spacing
θ	angle between the incident beam and the reflecting plane
L	wavelength
a_o	lattice parameter
h,k,l	Miller indices
R	camera to specimen distance
S	radius of the diffraction circle
a	angle between the incident beam and the diffracted beam
ψ	angle between the incident beam and the normal to the specimen surface
p	subscript indicating perpendicular direction
v	Poisson's ratio
E	Young's modulus of elasticity
s	stress
e	strain

SUMMARY

OBJECT:

The X-ray diffraction method of stress measurement is the only known means of determining absolute stress magnitudes without measurements in the unstressed condition. It is the objective of this thesis to investigate the feasibility of using this method in analysis of naval structures both aboard ship and on models.

METHOD:

X-ray waves of certain elements are comparable in length to atomic interplanar distances of common structural materials. The atomic interplanar distance of a given unstressed material is constant and may be determined easily. Using the diffraction property of X-rays, the atomic interplanar distance of the stressed material may be measured by recording the diffraction pattern on X-ray film. The difference between these two interplanar distances serves as a measure of the strain and may be converted, by Hooke's law, to a stress measurement.

CONCLUSION:

The use of this method for stress measurements aboard ship or on models is entirely practical provided X-ray equipment is designed for this specific purpose and a suitable method of surface preparation is developed.

RECOMMENDATIONS:

In using this method to investigate the stress distribution on an actual model, it immediately became apparent that X-ray equipment of a portable nature, constructed specifically for stress measurements, must be designed for actual measurements aboard ship. The proper preparation of the surface is a major factor in obtaining accurate results. The currently accepted procedure, a drastic acid etch with hand polishing followed by a mild acid etch, is a long, tedious process not particularly adaptable to field use. Some experimentation was conducted in an effort to reduce the time and labor involved in surface preparation. A reasonable technique was developed, but it is felt that further investigation would result in an improved technique.

INTRODUCTION

Stress intensity is a basic concern in naval structures since as a criterion it measures the success of any structure. Accurate evaluation of magnitudes in any and all parts of structure is vital, yet under many conditions measurement is not possible at present with the methods used in the Navy. The authors felt that an endeavor aimed at increasing the possibilities of accomplishing stress measurement would be worth the effort. Accordingly, this thesis attempts an investigation of the X-ray diffraction method of stress measurement, a method which obviates destructive test and renders absolute magnitudes without unloading.

The viewpoint throughout this investigation will be that of the naval engineer and not that of the physical metallurgist. The intent is to determine the adaptability of the method to use by the naval engineer, with an eye toward spotlighting the advantages and overcoming the disadvantages encountered. It is earnestly hoped that this thesis focuses attention upon the X-ray diffraction method and provides the full background necessary to any who would use this method in the Navy.

HISTORICAL BACKGROUND

Stress measurement based on the diffraction of X-rays had its first beginnings some two decades past. Lester and Aborn(1), in 1925, demonstrated that the spacing

of the atomic planes in a crystal is altered by stresses applied to the crystal. This spacing acts as a gage length and changes in this length actually constitute the elastic strains of a stressed material. They further introduced the use of this change as a means for determining stress through X-ray diffraction methods. In 1930 and 1931, German investigators(2) applied the precision back-reflection camera to the problem and succeeded in obtaining accuracy comparable to mechanical strain gages, but their methods produced only the sum of the principal stresses in the surface of the material. Development was rapid, however, and within five years Barrett and Gensamer(3), in this country, and Giesen, Glocker and Osswald(4)(5), in Germany, had succeeded in developing methods which permitted determination of single stresses from exposure of the material in the stressed state alone, the unstressed value of the interplaner spacing being determined from two measurements on the stressed material.

By this time several investigators(6) were attempting to establish the accuracy of this method by measuring the stress in tensile or bending test specimens and comparing values thus determined with the calculated stresses. Invariably X-ray stresses were lower than calculated stresses. Since the mechanical stress was an average over the whole cross-section area, whereas the X-ray stress was that measured from several crystals oriented in certain directions, it was assumed that the discrepancy was

due to anisotropy of the individual crystals. It was concluded that by altering the empirical values of the modulus of elasticity and of Poisson's ratio, reasonable agreement could be obtained between X-ray determined stresses and mechanically measured stresses. However, opposing this, Moller and Strunk(7) determined that experimental errors were greater than any discrepancies due to anisotropy.

The most recent work in this category, by Ersoz(8) in 1944, indicates that under certain conditions the values of the elastic modulus and Poisson's ratio, as commonly accepted, will give reasonably accurate X-ray stress values. His most important conclusion was that surface preparation had a definite effect upon X-ray stress values and, since none of the previous literature gave any indication of the surface preparation accomplished on test specimens, preparation methods may have been the cause of the discrepancies. This is a most important conclusion.

Theoretical development beyond this point seems to have been limited to refinement and no recent literature was uncovered having indication of important development of the method itself.

Application of the method which has been recorded has been confined to the study of residual stresses in welds(9). The nature of the stress measurement problem in welds and the favorable conditions existing in weld material readily invite the use of this method of measurement.

The preclusion of other applications during the unprecedented use of welding in the war years is understandable. No literature was uncovered concerning other applications of X-ray stress measurement.

DESCRIPTION OF EQUIPMENT

The equipment necessary, in general, is simple, consisting of few parts. An X-radiation tube is required, mounted so that it can be conveniently powered and cooled, and capable of intense monochromatic radiation. Windows must be arranged in the tube head to permit the egress of the X-ray beam.

The camera is circular, consisting of a disc back and faceplate with a small hole at the center. In addition, ports are cut in the faceplate at quadrant points and backed with light-tight paper, so that only four arcs of the reflected cone of rays are recorded on the film. The camera is mounted on the tube head by means of a mounting block which supports a hollow shaft. Disc and faceplate must be exactly perpendicular to the axis of the shaft. A collimating pinhole is placed inside the shaft to limit the beam and focus the diffraction image to a sharp line. Means must be provided for oscillating the camera through an angle less than 30 degrees. The X-ray beam passes through the hollow shaft and the hole in the camera to the specimen.

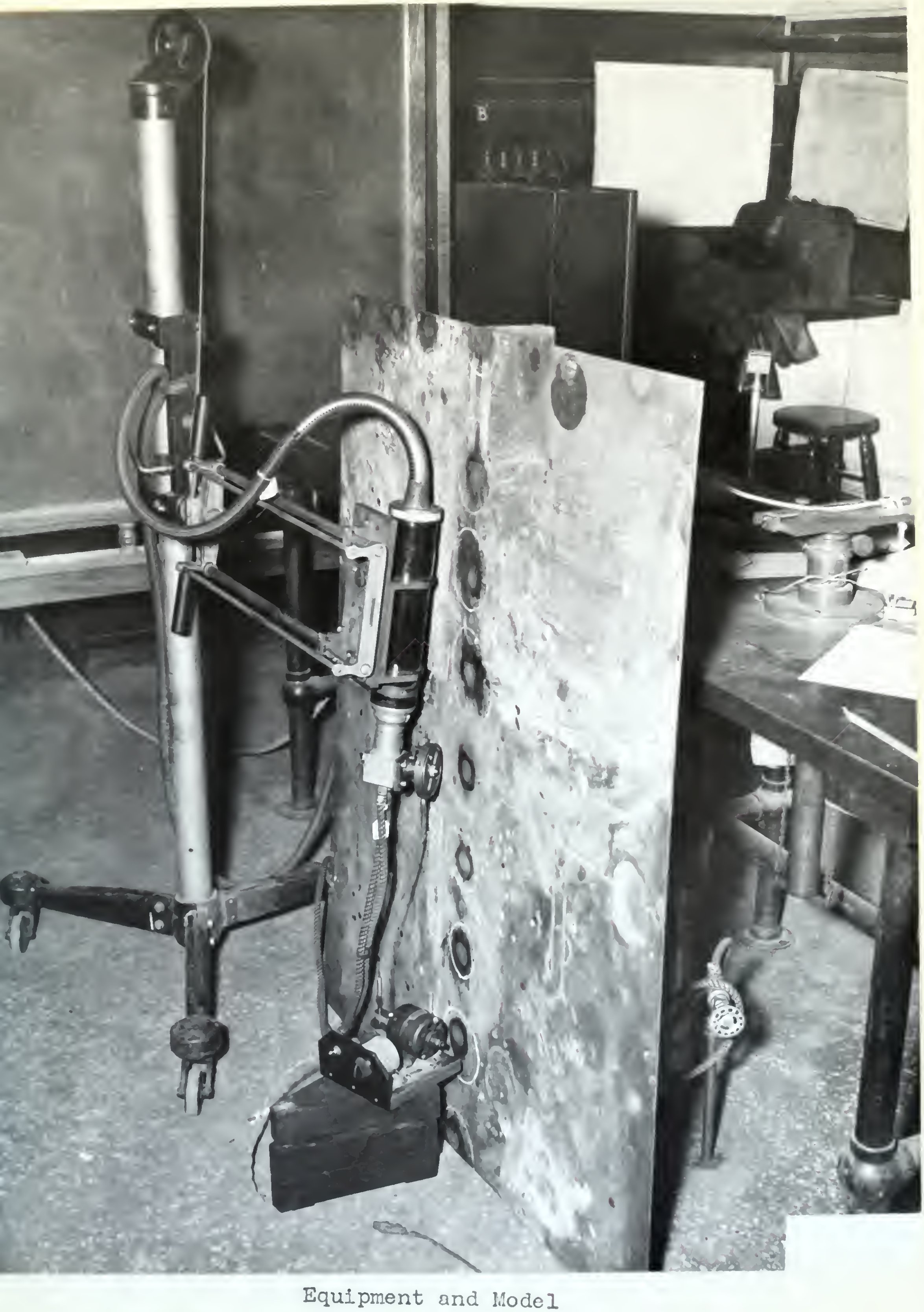
In this work we used a tube manufactured by the Machlett Laboratories, possessing a ray-proof, shockproof housing integral with the tube body, with the added feature

of being "sealed off." Thus continuous evacuation was not required, as would have been were the tube not so. X-rays were available at the snap of a switch without danger - a decided advantage to inexperienced operators. Water cooling was supplied via flexible leads with a thermostatic device which turned off the tube if cooling water failed. An associated transformer supplied the high voltage required.

Mounting is particularly important if the structure to be measured is large or immovable. In this work the tube was mounted on a stand consisting of a column supporting an adjustable carriage. Mounting the tube upon this carriage permitted movement of the tube and thus the beam direction in all planes. The photographs (Figures I, II) show this equipment and mounting.

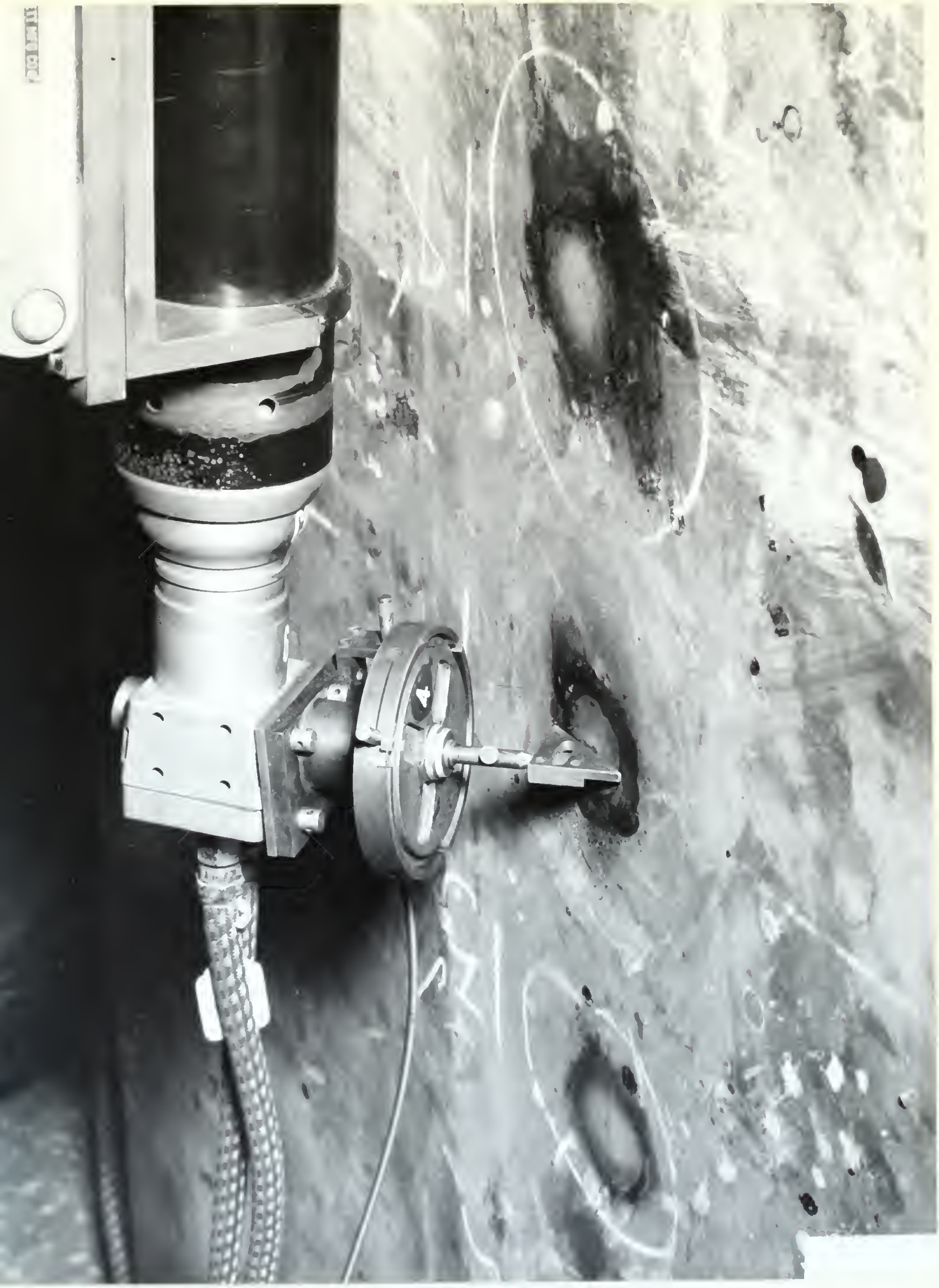
Inasmuch as alignment of the plane of the camera with the plane of the specimen is important, a device to accomplish this is required. A simple one consists of a small telescopic rod, with a pointer attached, of such diameter and tapered so as to fit into the hollow shaft of the camera mounting block. The extended length should be such that when the device is in place and the pointer just touches the specimen, desired specimen-to-film distance approximately exists. Upon the shaft of the pointer is then mounted, with spring clip, a small angle plate, the edge of which is perpendicular or at 45 degrees to the pointer axis. Specimen and camera can be thus aligned either parallel or at an angle of 45 degrees in

FIGURE I



Equipment and Model

FIGURE II



Alignment of Camera

any plane. Figure II shows this device.

THEORY

Inasmuch as this presentation is directed toward the practical aspects of X-ray diffraction, the theory necessary to the understanding of the method is recorded here briefly and simplified, for the naval engineer. For rigorous development and explanation of this theory, reference should be made to several of the texts listed in the Bibliography, and to the supplementary Introduction.

The X-ray diffraction method of stress measurement depends upon the property of X-rays that, if directed upon a substance, crystalline in nature, the X-rays are scattered by the atoms of this substance. If the atoms are arranged in a regularly repeating pattern, the scattered X-rays cooperate to build up diffracted waves.

The fundamental theories of diffraction apply to these waves. Consider a series of parallel planes with an incident ray, L_1L_2, striking at an angle Θ, and of wavelength L (Figure III). It can be seen that for reinforcement $2d \sin \Theta = n L$ where n is an integral number. This is the Bragg equation, which defines the distance, d, between planes in terms of the constants of the incident ray.

$$d = \frac{n L}{2 \sin \Theta}$$

The structure of any metallic substance is one of regularly spaced atoms within a crystal. Planes of atoms,

FIGURE III

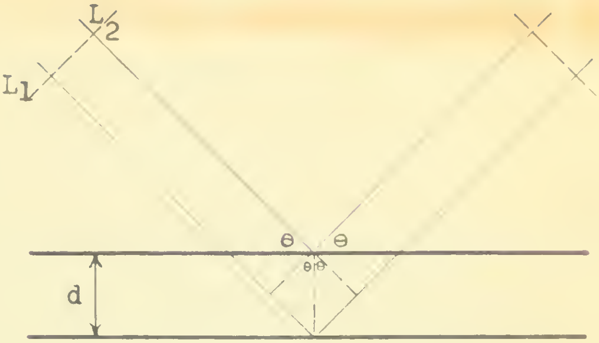


ILLUSTRATION OF BRAGG'S LAW OF REFLECTION
FROM PLANES OF ATOMS

FIGURE IV

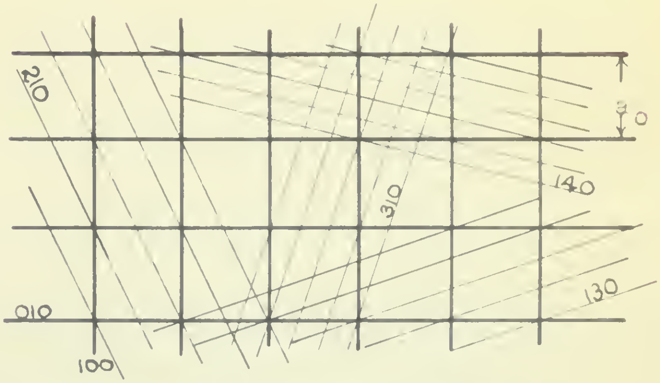


ILLUSTRATION OF MILLER INDICES

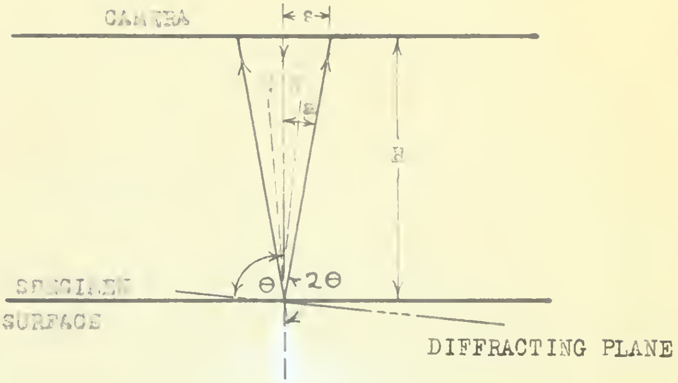
therefore, have a constant characteristic spacing in any direction when the metal is unstressed. An incident X-ray, since the wavelength is of the same order of magnitude as the inter-atomic spacing, will be reflected from these atomic planes in exactly the manner as depicted in Figure III. Therefore, we may use the Bragg equation to determine the existent value of the spacing between the planes of atoms.

It must be kept in mind that the distances between atoms and the distances between atomic planes differ. Although the distances between all atoms of an unstressed metal are the same (lattice parameter, a_o), the distances between atomic planes differ according to which atoms make up the planes. This can be seen from Figure IV. A system of lattice coordinates known as the Miller indices is used to designate planes. These coordinates are based on the number of parts into which the planes divide the lattice parameter. The interplaner distance is a function of the Miller indices (h, k, l):

$$d = \frac{a_o}{\sqrt{h^2 + k^2 + l^2}}$$

The spacing of the atomic planes in any direction varies with the state of stress of the metal in that direction. By elastic theory, the ratio of the change in d to d itself (or strain) is proportional to the stress of the metal. This provides the basis upon which the method is developed, since the interplaner distance acts as a small strain gage.

FIGURE V



DETERMINATION OF TAN 2α

Differentiating the Bragg equation:

$$\Delta d = -\frac{L}{2} \csc \theta \cot \theta \Delta \theta$$

$$\frac{\Delta d}{d} = -\cot \theta \Delta \theta$$

By means of the above equation the value of the strain can be determined from the change in the incidence angle. Inasmuch as direct measurement of the change in the incidence angle is impractical, it is necessary to find some other menas of determining this change. Consider Figure V.

$$\tan a = \frac{S}{R}$$

$$\tan (180 - 2\theta) = \frac{S}{R}$$

$$\tan 2\theta = -\frac{S}{R}$$

$$S = -R \tan 2\theta$$

$$\Delta S = -2R \sec^2 2\theta \Delta \theta$$

$$\Delta S = +2R \sec^2 2\theta \tan \theta \frac{\Delta d}{d} \quad . \ . \ . \ . \ . \quad (1)$$

The value of the strain, $\frac{\Delta d}{d}$, is thus proportional to the change in the radius of the diffraction circle recorded on the film. The value, ($+2R \sec^2 2\theta \tan \theta$), is called the magnification factor. It is considered constant for small changes in θ. The strain measured in this manner is actually that along N but for small angles, $\frac{a}{2}$, involved, the strain is considered along the normal to the surface.

From elastic theory, strain in a given direction resulting from stresses in a plane perpendicular to this direction is given by:

$$e_z = - \frac{v}{E} (s_x + s_y)$$

Also, by definition:

$$e_z = \frac{d_p - d_o}{d_o} = \frac{\Delta d}{d}$$

where d_p is the interplaner distance measured in the stressed condition and d_o that in the unstressed condition.

$$\Delta S = + \left[2R \sec^2 2\theta \tan \theta \right] \left[- \frac{v}{E} (s_x + s_y) \right]$$

$$s_x + s_y = \frac{- E \Delta S}{2vR \sec^2 2\theta \tan \theta}$$

or,

$$s_x + s_y = K \Delta S \quad . . . . \quad (2)$$

where K = pounds/inch^2 - mm.

ΔS = S(stressed) - S(unstressed) in mm.

This provides the sum of the principal stresses. It requires a measurement of d in the stressed and in the unstressed conditions.

For most conditions of use, it is desirable that a method be developed requiring only the measurement of d in the stressed condition and providing the stress in one direction alone.

From the "ellipsoid of strain,"

$$e_p - e_\psi = - \frac{1 + v}{E} s_x \sin^2 \psi$$

where e_p is the strain measured in the normal to the surface and e_ψ is the strain measured at some angle ψ but in the plane defined by the normal and the x direction.

$$e_p - e_\psi = \frac{d_p - d_o}{d_o} - \frac{d_\psi - d_o}{d_o} = \frac{d_p - d_\psi}{d_o} = \frac{d_p - d_\psi}{d_p} = -\frac{1+v}{E}\, s_x \sin^2 \psi$$

Since the difference $d_p - d_\psi$ is small compared to either d_o, d_p, or d_ψ, we may substitute d_p for d_o with negligible error. Substituting this in equation (1):

$$S_p - S_\psi = \left[\, 2R \sec^2 2\theta \tan \theta \,\right]\left[-\frac{1+v}{E}\, s_x \sin^2 \psi \right]$$

$$s_x = \frac{E\ (S_p - S_\psi)}{2(1+v)\ R \sec^2 2\theta \tan \theta \sin^2 \psi}$$

or

$$s_x = F\ (S_p - S_\psi)\ \ldots\ldots\ldots\ldots\ldots \quad (3)$$

where F = pounds/inch^2 - mm.

$S_p - S_\psi$ = mm.

This equation meets the requirements of permitting calculation of a single stress from a perpendicular and an angle measurement of d in the stressed condition alone.

MODEL

The model used in this investigation was designed to present a simple problem of some value and at the same time to demonstrate the particular advantages of using this method of stress measurement. A dimensioned sketch of the model is shown in Figure XII and a photograph is presented in Figure XII-A. The plate was 5 pound (1/8") medium steel having the following specifications:

Federal Stock Catalogue
#48-S-5 Grade M

> These carbon steel sheets for hull construction work have an average minimum tensile strength of 60,000 pounds per square inch and maximum carbon content of 0.31%. These sheets can be readily fabricated and welded.

The Tee stiffener was a 4" x 2 3/8" T cut from a 4" x 2 3/8" x 7.7# I. The model was fabricated by the Boston Naval Shipyard.

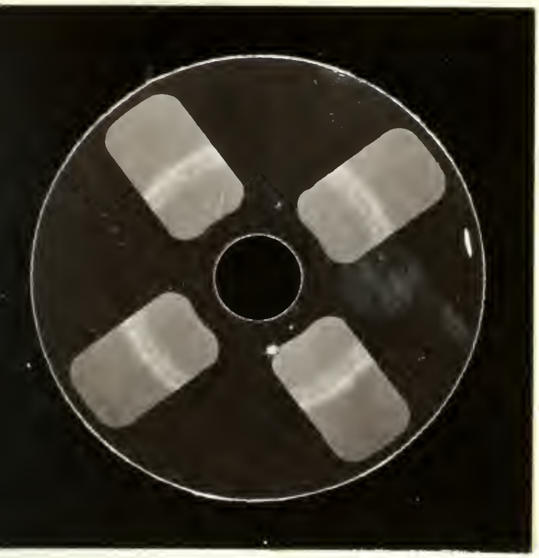
PROCEDURE

If the reflected X-ray beam were allowed to strike stationary X-ray film a considerably diffused diffraction circle would result. In order to eliminate this diffusion and to give a distinct diffraction circle which is more easily read, the camera was oscillated through an angle of about 30 degrees by means of a small motor. Figure VI shows a diffraction circle caused by not oscillating the camera and Figure VII shows the diffraction circle from the same point when the camera is oscillated.

In order to obtain a true circle from the diffracted rays the X-ray beam must be perpendicular to the camera as it passes through the camera. The camera is mounted on the X-ray tube by means of four screws in oversized holes, thus permitting small movements of the camera relative to the tube. Perpendicular pictures were taken of unstressed tungsten powder and diameters 90 degrees apart were measured. When movement of the camera brought these two diameters within 0.1 millimeters the camera was assumed aligned.

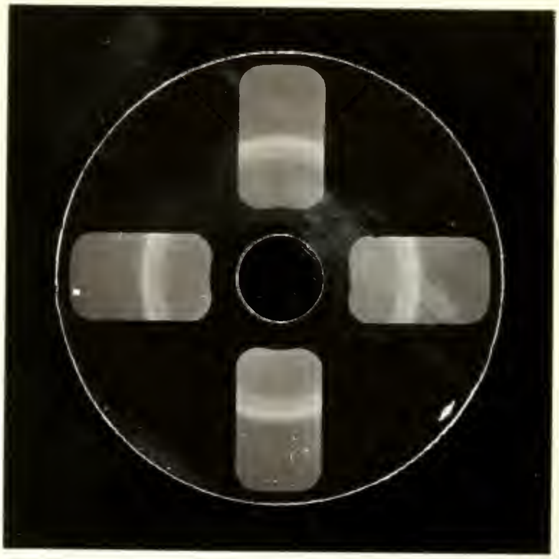
The surface preparation technique employed to remove the surface layer was a combination of strong acid etch and electro-polishing. The acid used was a 30% solution of concentrated nitric acid in water. The electrolyte employed was nital (6% nitric acid - 94% alcohol). Originally, the technique employed by Ersoz(8) was used, but this was not particularly adaptable to use in the field

FIGURE VI



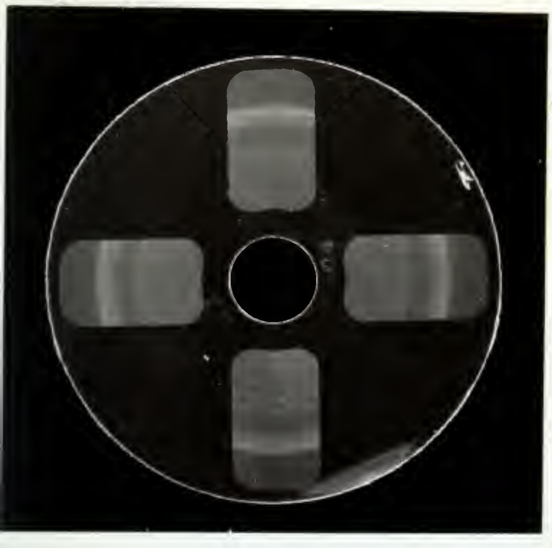
DIFFRACTION CIRCLE RESULTING FROM NON-OSCILLATED EXPOSURE

FIGURE VII



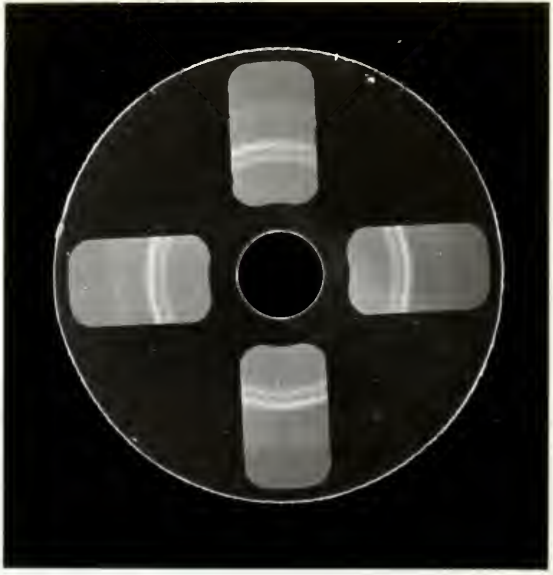
DIFFRACTION CIRCLE RESULTING FROM OSCILLATED EXPOSURE

FIGURE VIII



FILM RESULTING FROM EXCESSIVE TUNGSTEN LAYER

FIGURE IX



FILM RESULTING FROM INSUFFICIENT TUNGSTEN LAYER

due to the time and labor involved. The procedure finally used reduced the time involved considerably and practically eliminated the labor. The time involved is dependent upon the amount of material to be removed.

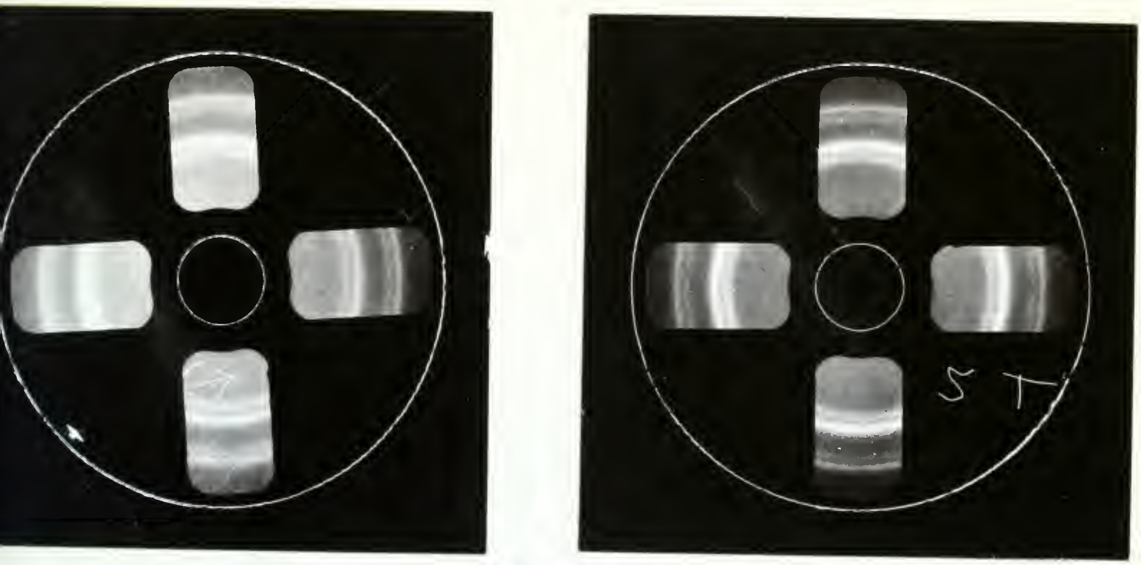
As may be seen from the stress equation, the distance from the camera to the model is critical and must be determined with great accuracy. This distance may be measured with a pair of inside micrometers, but such a procedure has not proved too satisfactory. Another and more satisfactory method of determining this film-to-specimen distance is to use a metallic powder dusted on the surface of the model. This procedure results in two concentric diffraction circles on the film. Knowing that the metallic powder is in the unstressed condition, the diameter of its diffraction circle may be determined for any selected film-to-model distance. By comparison of this diffraction circle diameter with that actually obtained, all film readings may be corrected to the selected film-to-model distance. This method of determining film-to-model distance has decided advantages over using micrometers. Readings are automatically corrected for any film size variation in the developing process or due to temperature variations. It allows the constant in the stress equation to be calculated in advance. A permanent comparison is obtained on the film itself, thereby permitting the results to be read at any time. Powdered tungsten was used throughout this investigation since it gives a diffraction circle sufficiently great in

diameter as not to interfere with the iron diffraction ring and yet small enough to remain on the film. A light layer of vaseline was applied to the surface of the area to be investigated. Tungsten powder was then dusted on the surface with a small camel's hair brush. Care must be taken in applying the tungsten, as too much will obscure the iron ring and too little will make it difficult to determine the film-to-specimen distance. Figures VIII and IX illustrate these two conditions. The film-to-model distance selected for the determination of the constant in the stress equation was such as to give a tungsten diameter of 50 millimeters.

The X-ray tube and camera were mounted on the stand pictured in Figure I which allowed movement in all directions. The camera and tube were aimed by means of the distance piece and angle indicator shown in Figure II. Forty-five kilovolts with a current of 10 milliamperes was used. An exposure time of 12 minutes was found to give the most satisfactory results.

Having completed the exposure, the film is developed using standard photographic practices. Distances on the film are determined by the use of a measuring box. This device consists of a box topped by a frosted, light backed glass on which is mounted a scale (capable of readings to 0.020 mm.) and a traveling hair line. Readings are obtained by placing the hair line at the center of the diffraction line. Several readings were made of each line and

FIGURE X



Angle Exposure

Perpendicular Exposure

the results averaged.

As has been pointed out, in order to determine the stress in any one direction, two pictures must be taken, one perpendicular to the surface and one at an angle. The angle used was 45 degrees corrected by the angle between the incident ray and the normal to the reflecting plane. From these two pictures the difference $S_p - S_\psi$ in the stress equation was measured. The diffraction circle obtained from the angle picture is not an exact circle but has become slightly eliptical and, in addition, the side of the film closest to the camera gives a line which is narrower and more distinct. Figure X shows an angle picture as compared to a perpendicular picture.

In order to avoid the difficulties which would be encountered if it were necessary to measure the diameters of the diffraction circle directly, the Δ shown in Figure XI is read. The difference between the Δ read from the perpendicular film and that read from the angle film is exactly equal to $S_p - S_\psi$.

Since

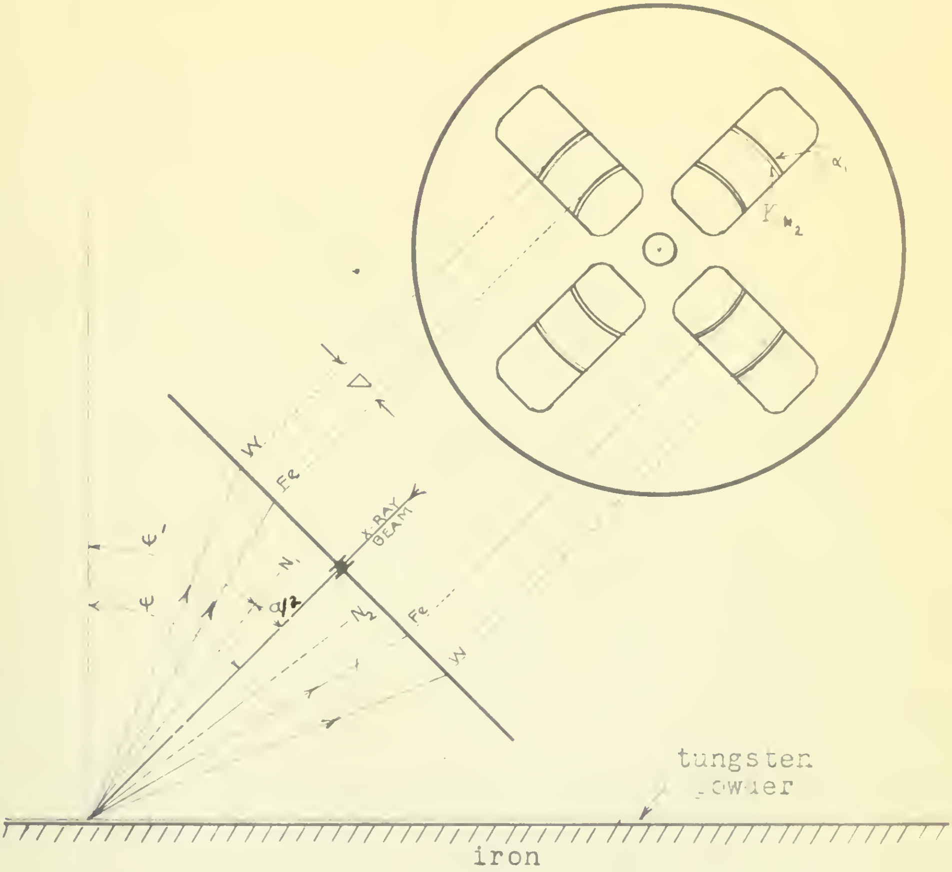
$$2S_p = 2S_w - 2\Delta_p$$

$$2S_\psi = 2S_w - 2\Delta_\psi$$

All values having been corrected to the standard S_w, subtracting one equation from the other gives

$$S_p - S_\psi = -(\Delta_p - \Delta_\psi) \quad . \; . \; . \; . \; . \; . \; . \; . \; (4)$$

FIGURE 7

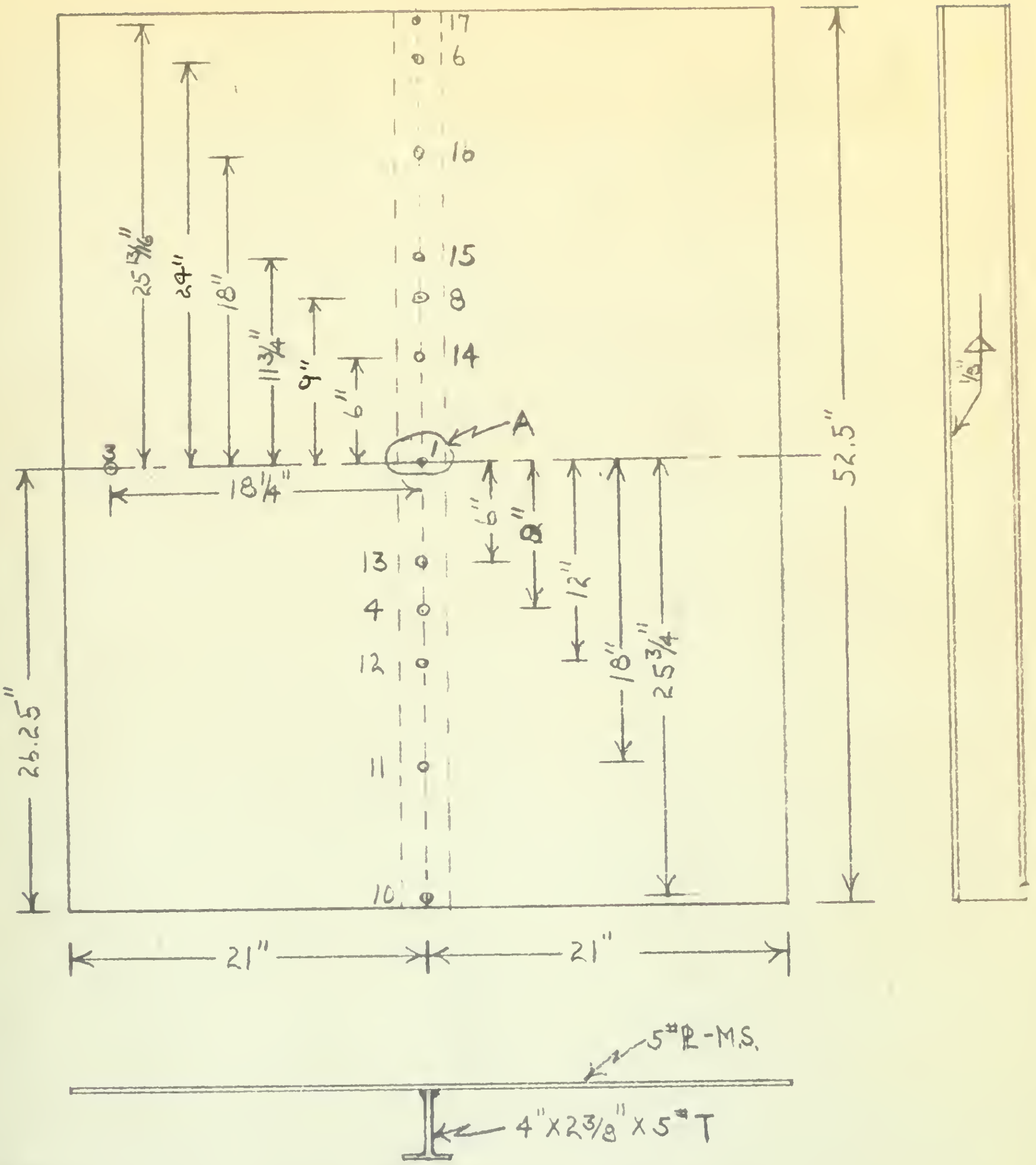


CAMERA INCLINED AT 45°

This method of determining the difference in the radii of the diffraction circles was used throughout the procedure.

FIGURE XII

SKETCH OF MODEL SHOWING POSITION OF POINTS



Expansion of "A"

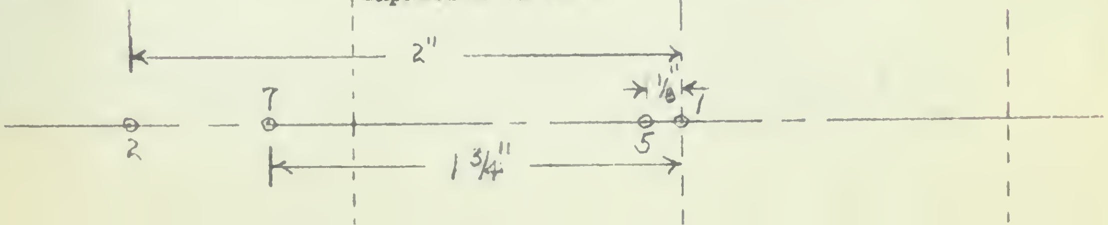
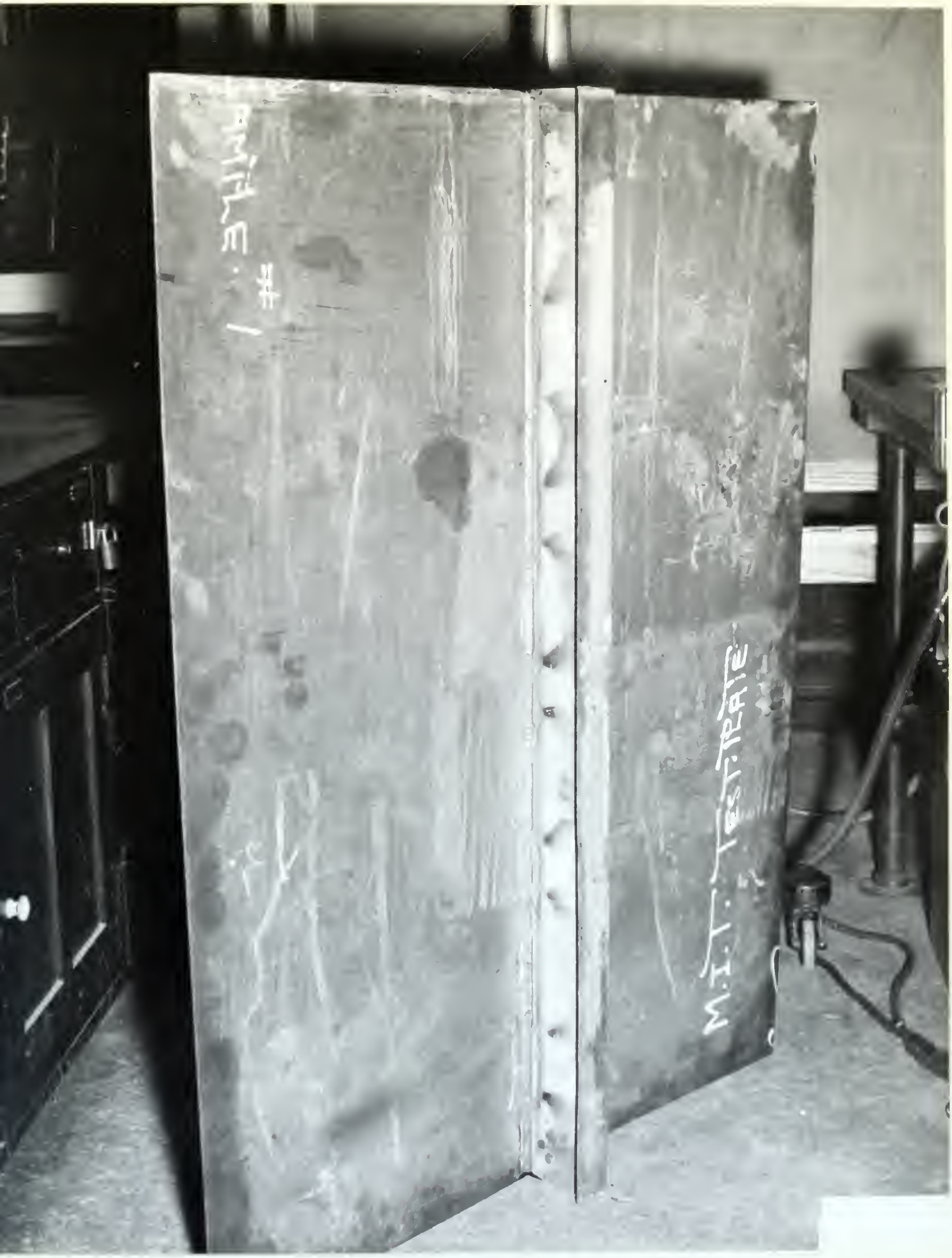


FIGURE XIII-A



Model

TABLE I

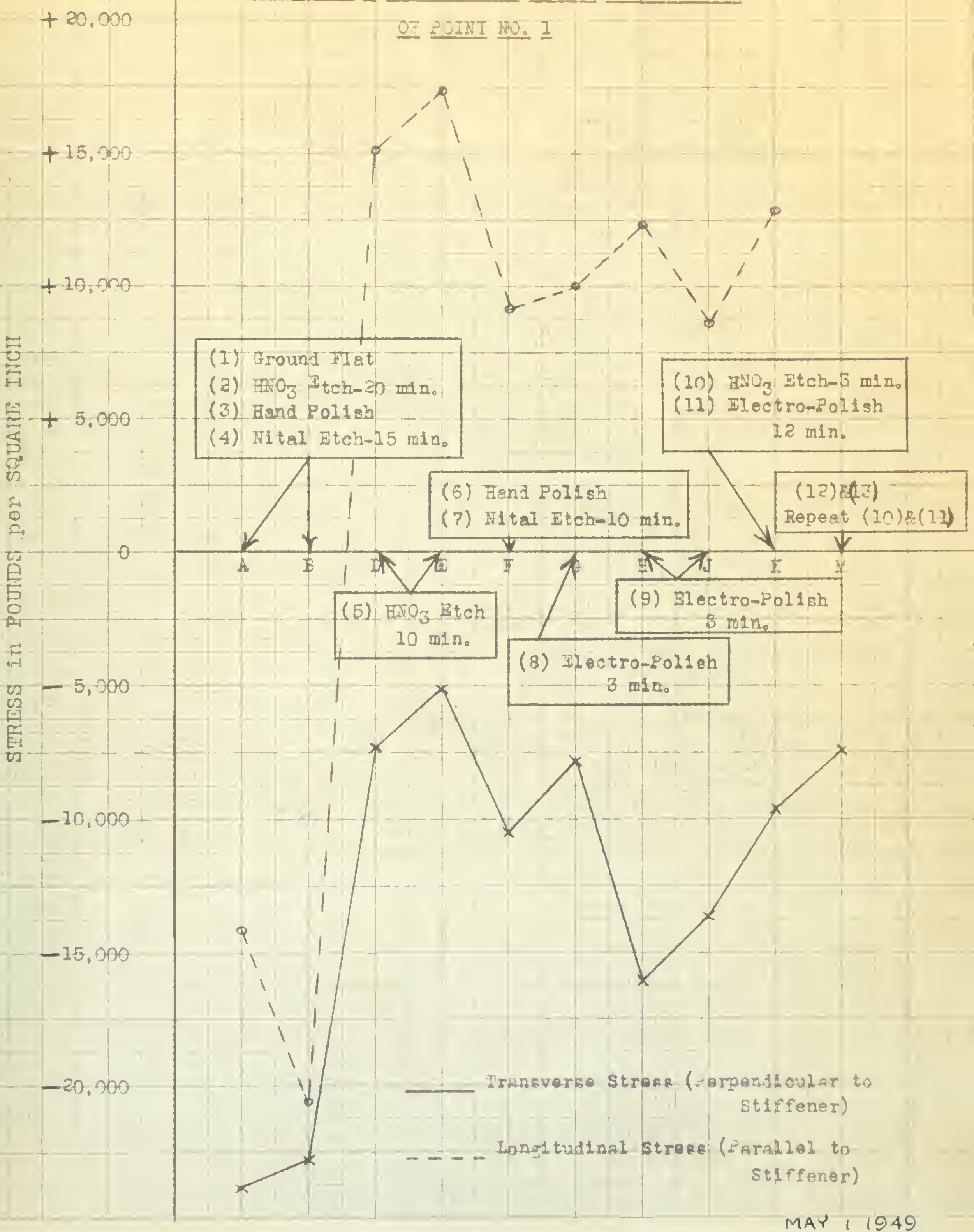
STRESS MEASUREMENT DATA

	PERPENDICULAR (⊥)				TRANSVERSE (A)						LONGITUDINAL (L)					
Point	$2S_w$	Δ'_p	Corr.	Δ_p	$2S_w$	Δ'_A	Corr.	Δ_A	$\Delta_p-\Delta_A$	s_A	$2S_w$	Δ'_L	Corr.	Δ_L	$\Delta_p-\Delta_L$	s_L
1-A	54.74	5.71	-0.50	5.21	54.92	6.31	-0.58	5.73	-0.52	-23,798	53.88	5.95	-0.43	5.52	-0.31	-14,187
1-B	53.79	5.59	-0.39	5.20	52.48	5.98	-0.28	5.70	-0.50	-22,883	52.24	5.90	-0.25	5.65	-0.45	-20,595
1-D	51.49	5.80	-0.17	5.63	52.66	6.10	-0.31	5.79	-0.16	- 7,323	52.80	5.60	-0.30	5.30	+0.33	+15,103
1-E	52.62	5.91	-0.30	5.61	52.92	6.06	-0.34	5.72	-0.11	- 5,034	53.72	5.62	-0.39	5.23	+0.38	+17,391
1-F	51.71	5.72	-0.19	5.53	51.72	5.96	-0.20	5.76	-0.23	-10,526	50.50	5.28	-0.05	5.23	+0.20	+ 9,153
1-G	51.74	5.74	-0.19	5.55	50.84	5.82	-0.10	5.72	-0.17	- 7,730	51.44	5.48	-0.15	5.33	+0.22	+10,069
1-H	50.40	5.48	-0.04	5.44	49.22	5.70	+0.09	5.79	-0.35	-16,018	51.42	5.32	-0.15	5.17	+0.27	+12,355
1-J	49.45	5.46	+0.06	5.52	50.18	5.84	-0.02	5.82	-0.30	-13,730	49.76	5.30	+0.03	5.33	+0.19	+ 8,696
1-K	50.04	5.50	0.00	5.50	51.65	5.90	-0.19	5.71	-0.21	- 9,611	52.30	5.46	0.24	5.22	+0.28	+12,814
1-M	50.52	5.64	0.06	5.58	51.90	5.96	-0.22	5.74	-0.16	- 7,323						
2	53.30	5.62	-0.35	5.27	52.96	6.08	-0.34	5.74	-0.37	-16,933						
3	52.15	5.75	-0.24	5.51	52.28	5.66	-0.25	5.41	+0.10	+ 4,577	52.42	5.72	-0.26	5.46	+0.05	+ 2,288
4	52.37	5.72	-0.26	5.46	52.96	6.70	-0.38	6.32	+0.14	+ 6,407	52.60	5.36	-0.26	5.10	+0.36	+16,476
4-A	48.13	5.26	+0.20	5.46	50.98	5.94	-0.11	5.83	-0.37	-16,933	50.44	5.38	-0.05	5.33	+0.13	+ 6,850
4-B	50.70	5.54	-0.08	5.46	46.38	5.48	+0.43	5.91	-0.45	-20,595	51.44	5.38	-0.15	5.23	+0.23	+10,526
5	48.63	5.28	+0.15	5.43	52.52	6.13	-0.29	5.84	-0.41	-18,764	51.84	5.60	-0.20	5.40	+0.03	+ 1,373
6	52.48	6.14	-0.29	5.85	50.48	5.54	-0.05	5.49	+0.36	+16,476	53.80	5.96	-0.42	5.54	+0.31	+14,187
7	51.04	5.74	-0.12	5.62	52.08	5.90	-0.24	5.66	-0.04	- 1,831	52.32	5.66	-0.25	5.41	+0.21	+ 9,611
8	48.15	5.47	+0.21	5.68	50.28	5.46	-0.03	5.43	+0.25	+11,442	53.20	5.98	-0.36	5.62	+0.06	+ 1,373
8-A	50.82	6.20	-0.10	6.10	50.80	5.62	-0.09	5.53	+0.57	+26,087	50.72	5.48	-0.08	5.40	+0.70	+32,036
10	50.42	5.25	-0.04	5.21	49.72	5.72	+0.03	5.75	-0.54	-24,714	51.44	5.62	-0.16	5.46	-0.25	-11,442
11	48.66	5.50	+0.15	5.65	49.94	5.74	+0.01	5.75	-0.10	- 4,577	51.16	5.46	-0.12	5.34	+0.31	+14,187
12	50.00	5.70	0.00	5.70	50.36	5.98	-0.04	5.94	-0.24	-10,984	48.00	5.06	+0.21	5.27	+0.43	+19,679
13	50.96	5.97	-0.11	5.86	54.08	5.94	-0.45	5.49	+0.37	+16,933	49.96	5.36	0.00	5.36	+0.50	+22,883
13-A	50.27	5.80	-0.03	5.77	51.90	5.78	-0.21	5.57	+0.20	+ 9,153	52.28	5.66	-0.25	5.41	+0.36	+16,476
14	50.67	5.62	-0.07	5.55	52.00	6.08	-0.23	5.85	-0.30	-13,730	50.98	5.44	-0.10	5.34	+0.21	+ 9,611
15	50.54	5.73	-0.06	5.67	52.48	6.40	-0.30	6.10	-0.43	-19,679	49.64	5.32	+0.04	5.36	+0.31	+14,187
16	48.37	5.90	+0.20	6.10	50.90	5.82	-0.10	5.72	+0.38	+17,391	50.60	5.36	-0.06	5.30	+0.80	+36,613
17	50.96	5.44	-0.10	5.34	50.34	5.82	-0.04	5.78	-0.44	-20,137	50.30	5.52	-0.03	5.49	-0.15	- 6,865

FIGURE XIII

TRANSVERSE & LONGITUDINAL STRESS MEASUREMENTS

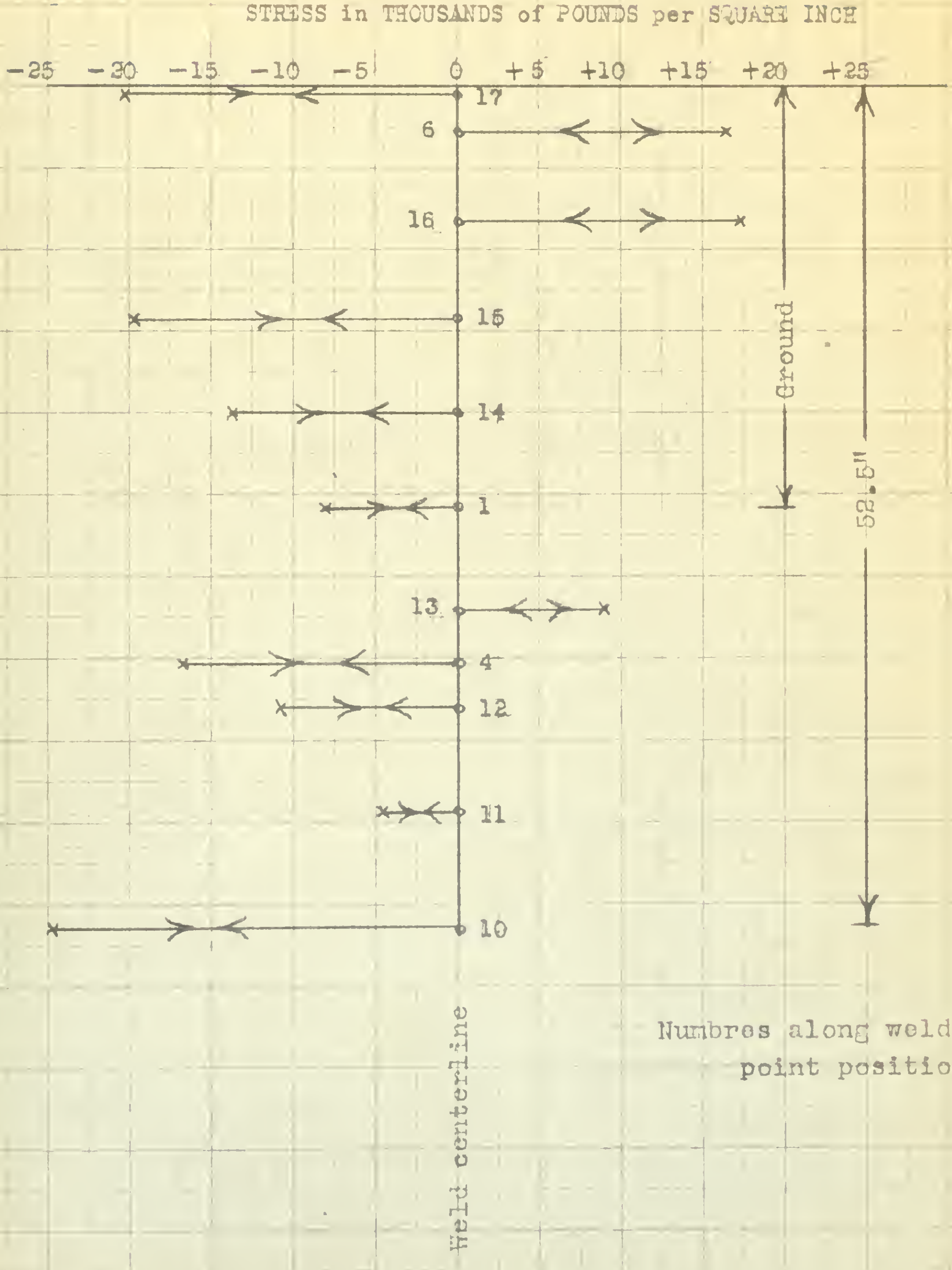
OF POINT NO. 1



MAY 1 1949

FIGURE XIV

TRANSVERSE STRESS IN PLATE ALONG WELD
ON SIDE OPPOSITE STIFFENER

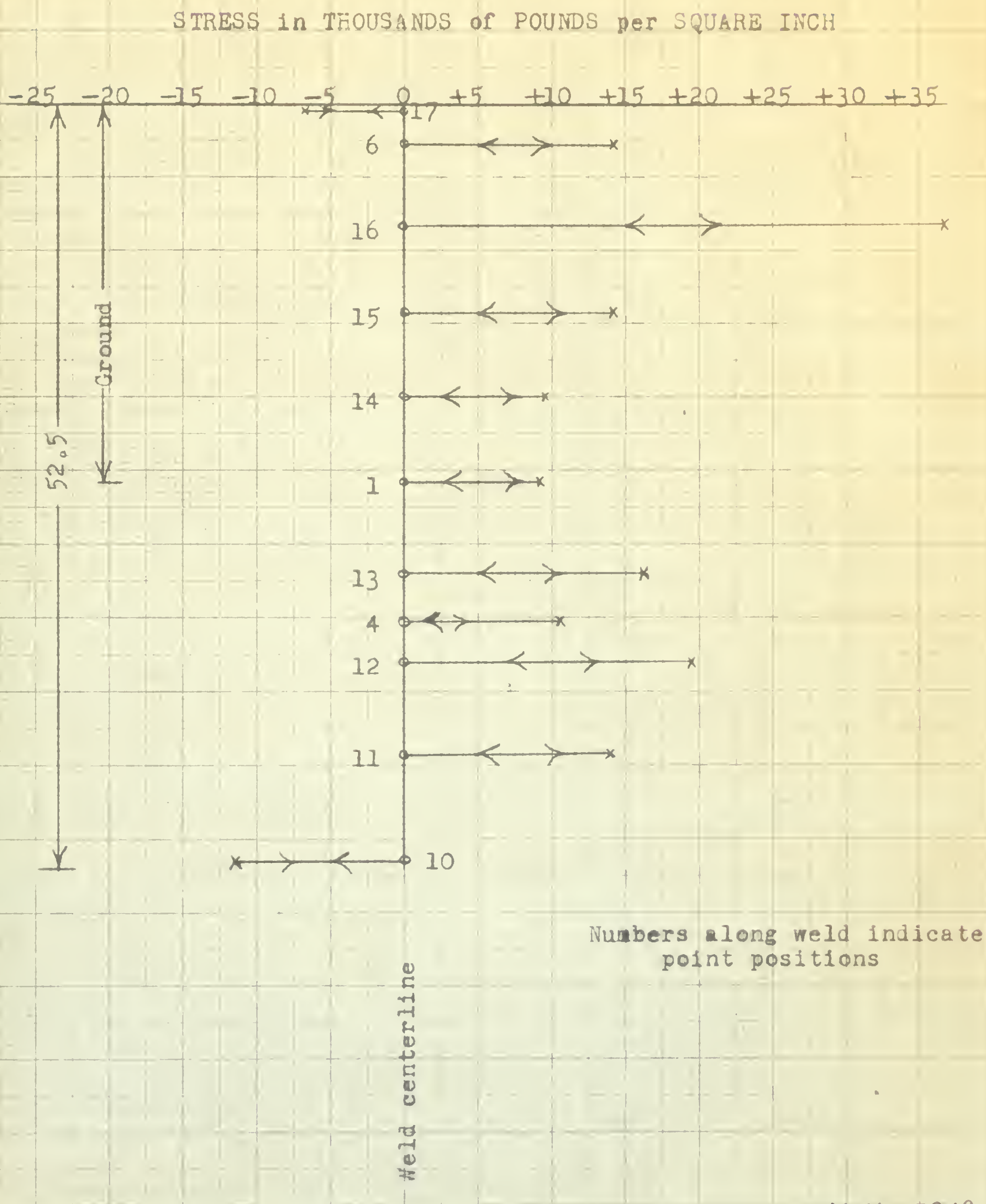


Numbres along weld indicate point positions.

MAY 1, 1949

FIGURE XV

LONGITUDINAL STRESS IN PLATE ALONG WELD ON SIDE OPPOSITE STIFFENER



Numbers along weld indicate point positions

MAY 1, 1949
mwB

TABLE II

SURFACE PREPARATION CALIBRATION

METHOD	TIME (Minutes)	READING (Inches)	DEPTH OF CUT (Inches)	CURRENT DENSITY (Amps/cm^2)
Start	0	0.120	-	-
30% Nitric Acid Etch(a)	20	0.117	0.003	-
30% Nitric Acid Etch	10	0.116	0.001	-
30% Nitric Acid Etch	10	0.115	0.001	-
30% Nitric Acid Etch(new)	10	0.113	0.002	-
Start	0	0.1105	-	-
Nital Etch(b)	20	0.1093	0.0012	-
Nital Etch	5	0.1088	0.0005	-
Start	0	0.120	-	-
Electro-Polish (Nital)	3	0.11925	0.00075	3
Electro-Polish (Nital)	3	0.11825	0.001	3
Electro-Polish (Nital)	3	0.11775	0.0005	3
Start	0	0.121	-	-
Electro-Polish (Nital)	15	0.120	0.001	4
Start	0	0.120	-	-
Electro-Polish (H_3PO_4)(c)	3	0.120	0	1.5
Start	0	0.120	-	-
Electro-Polish (H_3PO_4)	10	0.119	0.001	3
Start	0	0.121	-	-
Electro-Polish (H_3PO_4)	10	0.120^-	0.001^+	4
Start	0	0.121	-	-
30% Nitric Acid Etch	10	-	-	-
Electro-Polish (Nital)	10	0.115	0.006	3
Start	0	0.120	-	-
30% Nitric Acid Etch	10	-	-	-
Electro-Polish (H_3PO_4)	10	0.114	0.006	4
Start(d)	0	0.120	-	-
30% Nitric Acid Etch	5	-	-	-
Electro-Polish (Nital)	15	0.1105	0.0095	3
Start(e)	0	0.120	-	-
30% Nitric Acid Etch	3	-	-	-
Electro-Polish (Nital)	12	0.116	0.004	3

(a) 30% concentrated nitric acid, 70% water.
(b) 6% concentrated nitric acid, 94% alcohol.
(c) 30 parts by volume of sulphuric acid
70 " " " " phosphoric acid
10 " " " " water.
(d) This method used in preparing surfaces of ground area.
(e) This method used in preparing surfaces of area which had not been ground.

RESULTS AND DISCUSSION

In general, the results are adequate to permit formulation of conclusions as to the feasibility of using this stress measurement method. As previously pointed out, the model was designed to present residual stress which could not be determined by a non-destructive test. Unfortunately, it was not expected that the stress distribution would be so complex. Rather, simple tensile stresses were anticipated with sharp gradients across the plate in the vicinity of the weld. This complexity precluded the complete analysis of stress distribution in the plate. However, sufficient experience and data were obtained to point out the advantages and the disadvantages, and to indicate the requirements of equipment and technique necessary to adapt the method to efficient use in the field.

Alignment of the camera so that the X-ray beam was perpendicular to the plane of the camera was required in our equipment. In equipment specifically designed for stress measurement, this alignment need be done only once, at time of manufacture, and the camera attached permanently on the tube in the proper position. Thus, this procedure would be eliminated entirely in normal use.

Previous literature indicated the critical nature of the problem of surface preparation. Therefore, considerable attention had to be given to this phase of the method. It was expected that the plate had a layer of cold worked

material due to the rolling process and to the grinding which was performed to smooth off the plate in the weld vicinity. To determine actual plate stress, this layer had to be removed.

The procedure recommended by Ersoz, as described in Details of Procedure, was decided upon. Point 1 (plate center) was prepared and the measurements 1-A and 1-B in Table 1 and Figure XIII resulted. These exceeded greatly the anticipated values and it was concluded that the cold work layer had not yet been completely removed. Measurements 1-D and 1-E, made during the second preparation, after the drastic etch but before the hand polishing, confirmed the conclusion of Ersoz that measurements of the highly pitted surface resulting from drastic etching are considerably lower (i.e., toward zero) than the actual surface stresses. The measurement made after the remainder of Ersoz's procedure was carried out (1-F) was considered to be the best value of the stress existing at Point 1.

It was apparent at this stage that Ersoz's procedure, although satisfactory for laboratory use, was too long and too laborious a process to be readily used in the field.

The greatest difficulty in the Ersoz method lay in the hand polishing of the drastically etched surface. Such polishing had to be done with very fine polishing paper to avoid cold working again, and therefore required several hours. In an effort to overcome this disadvantage,

it was felt that an electro-etching process could be used to remove material reasonably rapidly, yet leave remaining an unpitted surface. Various electro-polishing solutions were calibrated, as indicated in Table II. It can be seen that considerable time-saving was realized as compared with the hours of hand polishing, and labor was reduced to an absolute minimum. The only advantage not realized was rapid removal of material. This suggests the possibility of developing an etching solution which does remove material rapidly.

Sufficient time was not available to continue the above research. As a final resort, a compromise method combining the use of the drastic etch to attain rapid material removal with the use of the electro-polish to attain a smooth surface was calibrated (Table II). As indicated in Table II, this combination provided the features desired of a surface preparation technique for field use. It was used throughout the remainder of the investigation.

Undoubtedly the single electro-etching process holds the best promise for a surface preparation method. Although the compromise method served our immediate purpose, it is felt that to adapt the X-ray method to general use the single electro-etch process should be developed.

In the process of testing the electro-etching solutions, further measurements were taken on Point 1. (1-G, 1-H, 1-J.) In addition, measurement of Point 5

(Figure XII) was made. The stress obtained for Point 5 indicates the extreme gradient present in the transverse direction. This gradient serves to explain the higher values for stress at Point 1, as determined by measurements 1-H and 1-J. The points actually measured were probably somewhat off-center. This demonstrates the necessity of establishing the point of measurement accurately and of accurately aiming the incident X-ray beam. Only when these positionings can be accomplished with precision can we expect reproducibility of results and determination of stresses across steep gradients. The unit used in this investigation did not permit such precision positionings. Contributing to this inaccuracy in positioning was the vibration of the mount introduced through the flexible shaft from the motor to the oscillating mechanism. In the design of X-ray stress measurement equipment, it is necessary to provide a stable mounting for the X-ray tube. Further, provision must be made for micrometer adjustment of the tube and mounted camera in three dimensions with respect to the foundation to permit accurate positioning.

The attainment of the necessary stability of foundation while maintaining portability is the only foreseeable difficulty in the design of X-ray equipment for shipboard measurement. The unit requires only 110 V. A.C. and a supply of cooling water, services which are generally available. There are presently on the market commercial forms of portable electro-polishing units entirely self-

contained which could be adapted to this work. Some further study and detailed design development should produce a portable unit having all the features indicated necessary by our experience.

The measurements taken at Point 1 (1-K, 1-M), using the combination of etch and electro-polish, gave values consistent with those obtained using the accepted method of etch, hand polish, and etch. This demonstrated that these measurements were true values of the stress in the plate within the accuracy of the method. As indicated by Figure XIII, accuracy throughout the investigation was within ± 1500 psi.

This points out the fact that the error in the X-ray method is dependent upon the error in reading the distances between the diffraction lines. This error in reading bears no relation to the distance between the lines, the reading error being of constant magnitude. Therefore, regardless of magnitudes of stresses measured, the error is constant. Thus, on a percentage basis, the error decreases as the measured magnitudes increase. The method has small percentage error at high values and larger percentage error as magnitudes decrease.

With the above accuracy limitations in mind, the values of the stress at the points indicated in Figure XIV and XV are considered good, with the exception of Points 10 and 17. Since both of these indicate compressive stress, longitudinally and transversely, it is suspected that cold

worked material exists at these points. Either surface preparation has not progressed deeply enough or the material is cold worked all the way through. Further investigation would seem desirable here.

It should be reiterated that the prime purpose of this investigation was not to investigate the stress distribution in a stiffened plate. This would have been a sufficient problem for an individual thesis. Rather, the plate served as a unique model having features which would best demonstrate the advantage of the X-ray method.

From the experience gained in conducting this investigation, we can draw certain conclusions regarding the advantages and disadvantages of using this X-ray technique. As previously mentioned, the method has long been established in determining residual stress since no unstressed measurement is required. This is particularly true when destruction for relief of such residual stress is impossible. In addition, inasmuch as the interatomic spacing is involved, the method determines the elastic stress even though plastic flow may have occurred. Any strain gage measurement could not make this distinction. The small size of the X-ray beam permits measurement of stress over an area far smaller than normal strain gages will permit, a definite feature in the case of steep stress gradients such as existed in our model. These features present a good case for the use of the method.

It is also obvious that certain inherent disadvantages exist. The accuracy of the method is dependent upon the accuracy with which distances between the diffraction lines can be read. The sharper the line, the more accurate is the stress determination. Since the sharpness of the lines depends upon the grain size of the metal, accuracy likewise depends on grain size. Accuracy thus would be a function of the physical state of the metal composing the structure and consideration must be given to thise in applying the method. It should be noted, however, that the plate employed in this investigation was taken from the normal stockpile of a naval shipyard and diffraction lines were excellent. Initial cost would be high for equipment, but certainly not prohibitive. Inasmuch as photographic means are employed to record the diffraction lines, certain amounts of time are required. Exposures of about 12 minutes were used throughout this investigation. A time factor far greater than that in strain gage methods thus exists. Finally, only surface stresses can be reasonably measured and to an accuracy which, on a percentage basis, increases as magnitudes increase. These factors constitute the negative case.

In considering the above factors, it becomes apparent that several of the disadvantages cannot be entirely overcome at the present stage of development of

the method. However, it is equally apparent that they are not disqualifying. Furthermore, no disqualifying feature in the technique was uncovered by our procedures for which we could not foresee a possible solution by proper design of equipment or development of field technique. Therefore, we are led to the positive conclusion that the method is entirely feasible for use in analyzing naval structure. In fact, the definite advantage of the method in analyzing actual naval structures subjected to loadings which cannot be reproduced in models and the analyzing of metal models of high degree of indeterminancy without resorting to plastics and photo-elasticity make the method worthy of consideration.

CONCLUSIONS

1. The X-ray diffraction method of stress measurement is entirely feasible for use in analyzing naval structures.

2. The method is particularly applicable to the analyses of naval structures which are subjected to loadings which cannot be reproduced in models and to analyses of metal models of a high degree of indeterminancy.

3. The method offers the following advantages:
   (a) Determination of absolute magnitudes of elastic stress without measurement in the unstressed condition.
   (b) Determination of stress over a small area, approximately one-eighth of an inch in diameter, presenting a distinct advantage in the case of steep stress gradients.

4. The method presents the following disadvantages:
   (a) Requirement of fine grain size in the metal comprising the structure being measured to attain accuracy.
   (b) Lesser value of accuracy on a percentage basis at lower stress magnitudes due to constant magnitude of error.
   (c) Requirement of greater time for measurement procedure than that required for strain gage measurement.

(d) Limitation of the stress values determined to the surface of the material measured.

5. The stress distribution in a plate in the vicinity of a welded stiffener is a highly complex one with a steep transverse gradient.

6. Present methods of surface preparation give accurate results, but are too long and laborious to be feasible in field use. The method employed in this investigation, employing a drastic nitric acid etch followed by electro-polishing, gives accurate results and is a satisfactory method for field use.

7. To adapt the X-ray method to use in naval structures, equipment must be specifically designed to such use. Particular features which must be incorporated into the design are:

(a) Provision of micrometer adjustment of tube and camera with respect to the foundation to permit accurate positioning.

(b) Provision of stable mounting and self-contained oscillating unit to avoid vibration of the incident X-ray beam.

Present commercial portable electro-polishing units can be employed. No service not already at hand aboard ship is required.

RECOMMENDATIONS

1. The single electro-etch process of surface preparation holds promise for minimizing the time and effort in this phase of the X-ray method. A continuance of research to develop a method and a suitable electrolyte is recommended.

2. An attempt at the design of equipment expressly for X-ray diffraction stress measurement is recommended. The possibility of mounting three tubes so aimed as to obtain the perpendicular, and the two angle exposures simultaneously, suggested itself to the authors. Time required would thus be cut to one-third the present time. In addition, an electro-polishing unit capable of polishing surfaces at any angle, including overhead, would be required. Actual details of suitable equipment, compact for easy portability, will require attention and development.

APPENDIX

SUPPLEMENTARY INTRODUCTION

X-RADIATION THEORY

X-radiation from a target metal consists of a continuous spectrum over a wide range of wavelengths with a superimposed line spectrum of high-intensity single wavelength components, such as is indicated in Figure XVI. Only after a certain critical voltage, unique with each target metal, is surpassed, will the characteristic lines appear. The intensity of these lines varies directly as the current through the generating tube and slightly less than the second power of the voltage applied to the tube. Each element has the same fundamental pattern but the relative position on the wave length scale is a function of the atomic number, heavier materials having the shorter wavelengths. Therefore, we have available high intensity characteristic rays of known wavelength from each metal. These rays are the ones used in X-ray methods of stress measurement. The series is limited at the lower range of atomic numbers by the fact that the long waves are absorbed by the X-ray tube windows while heavier elements give white radiation of such intensity as not to be useful when only single line radiation is desired. The normal range of wavelengths used is 0.56 Angstrom units to 2.29 Angstrom units, and metals giving these wavelengths are silver, molybdenum, copper, cobalt, iron and chromium.

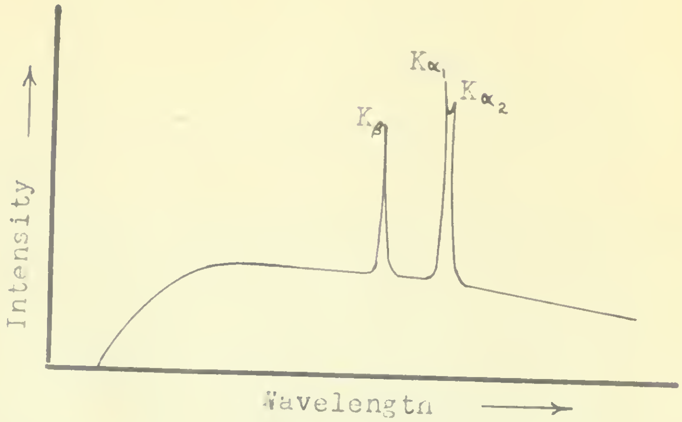
The explanation for the development of the characteristic rays is based upon the conception of the atom as a central nucleus with shells of electrons (K,L,M, etc.) surrounding the nucleus. Each shell exists at an energy level with the K shell immediately adjacent to the nucleus being at the highest energy level. The atom tends to remain in a state of minimum energy until energy is imparted to it from an outside source. When an electron stream is driven into the atom energy is imparted to the atom as a result of the ejection of an electron in one of the shells by the electrons in the stream. An electron from an outer shell moves into the shell from which the ejection occurs. This constitutes a sudden reversion to a lower energy state of the atom, and the atom in the process throws out a unit of energy, a quantum, in the form of radiation, the frequency of which is shown by $E = hf$, where E is the loss in energy, h is Planck's constant and f is the frequency. If a K shell electron is ejected, and the vacancy filled from the L shell, K_α radiation results. If it is replaced from the M shell, K_β radiation results, which differs from K_α by an increment of frequency proportional to the difference between the energy levels of the L and M shells. Had the ejection occurred in the L shell, L-series lines would develop. In Figure XVI , such lines would be at longer wavelengths, because of the lower energy levels involved, and thus to the right of the K-series lines shown.

Since the energy levels are discrete and sharp, the transitions between them give rise to sharp lines in the spectrum. However, there are complex secondary energy levels at each shell. The K level is a single one but the L level has three distinct levels and the M level five. Replacement of a vacancy in the K shell from the various L shell levels gives rise to a double K characteristic in the case of the cobalt radiation used in this work. It is shown in Figure XVI and can be noted in the photographs in Figures VI, VII, VIII, IX and X.

DIFFRACTION THEORY

Previous mention was made of the "scattering" of the X-ray beam by the atoms in the specimen surface. This phenomenon requires some explanation. The beam of X-rays passing over an atom accelerates the atom into a state of vibration. Such oscillation sets into motion a series of electromagnetic waves of the same frequency and wavelength as the incident beam. This is "coherent scattering." When this radiation is superimposed upon similar radiation from atoms in the same space lattice, reinforcement occurs and the diffracted beam is formed. "Scattering" is thus a transfer of radiant energy from the primary beam to scattered beams originating in the atoms of the material being measured. A second type, "modified scattering," occurs simultaneously, but has no bearing on stress measurement.

FIGURE XVI



TYPICAL X-RAY SPECTRUM OF A HEAVY METAL

WAVELENGTH REQUIREMENTS

In the Introduction it was pointed out that reinforcement of the wave occurred when $2d \sin \theta = nL$. In the subsequent development, the first order of reflection was assumed (i.e., $n = 1$) since this gives maximum intensity lines.

Consider the relation:

$$\frac{\Delta d}{d} = \tan \theta \, \Delta \theta$$

In measuring the strain by determining the change in the incidence angle, the maximum sensitivity will be attained when $\tan \theta$ is maximum and, therefore, when θ approaches 90 degrees.

It is thus desirable to employ an X-radiation of wave length approximating twice the interplaner distance.

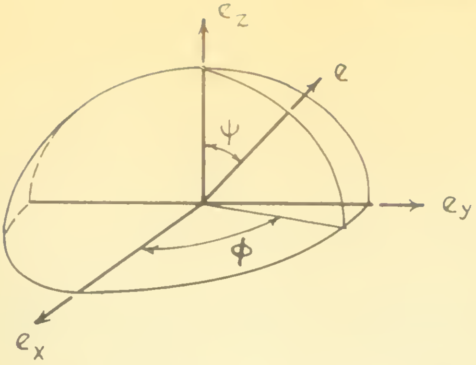
Since

$$d = \frac{a_o}{\sqrt{h^2 + k^2 + l^2}}$$

$$L \cong \frac{2\, a_o}{\sqrt{h^2 + k^2 + l^2}}$$

This establishes the requirements for the wavelength of the X-ray to be used in any stress measurement application.

[illegible]



EVELOPMENT OF "ELLIPSOID OF STRAIN"

ormal strain in any direction is given by the equation for t

ellipsoid of strain -

$$e = a_1^2 e_x + a_2^2 e_y + a_3^2 e_z$$

where;

$$a_1 = \sin\psi\cos\phi$$

$$a_2 = \sin\psi\sin\phi$$

$$a_3 = \cos\psi = \sqrt{1 - \sin^2\psi}$$

Assume $e_z = 0$,

$$e_\psi = \sin^2\psi\cos^2\phi\left[\frac{s_x}{E} - \frac{v}{E}s_y\right] + \sin^2\psi\sin^2\phi\left[\frac{s_y}{E} - \frac{v}{E}s_x\right] + \left[1 - \sin^2\psi\right]\left[-\frac{v}{E}(s_x + s_y)\right]$$

$$e_\perp = -\frac{v}{E}(s_x + s_y)$$

$$e_\perp - e_\psi = -\frac{\sin^2\psi}{E}\left[\cos^2\phi\, s_x - v\cos^2\phi\, s_y + \sin^2\phi\, s_y - v\sin^2\phi\, s_x + v\, s_x + v\, s_y\right]$$

$$e_\perp - e_\psi = -\frac{\sin^2\psi}{E}\left[s_x\,(\cos^2\phi - v\sin^2\phi + v) + s_y\,(-v\cos^2\phi + \sin^2\phi + v)\right]$$

$$= -\frac{\sin^2\psi}{E}\left[s_x\cos^2\phi\,(1+v) + s_y\sin^2\phi\,(1+v)\right]$$

$$= -\frac{\sin^2\psi}{E}\,(1+v)\left[s_x\cos^2\phi + s_y\sin^2\phi\right]$$

For this application, $\phi = 0$ to place e_ψ in the " XZ " plane, therefore:

$$e_\perp - e_\psi = -\frac{\sin^2\psi}{E}\,(1+v)\,s_x$$

DETAILS OF PROCEDURE

Since the X-ray tube used in this investigation was designed for uses other than stress measurements, it was necessary to mount the camera on the tube and to align it prior to stress measurements. Alignment was accomplished by measuring distances on a perpendicular picture taken of a specimen dusted with tungsten. Table III gives the 's obtained in aligning the camera used. Directions are taken as one faces the camera.

It was decided at the outset of the investigation to use the method of surface preparation proposed by Ersoz. The method consists of the following three steps: (1) a drastic acid etch (30% concentrated nitric acid in 70% water), (2) hand polishing with polishing cloth to a smooth, bright finish, and (3) a mild nital (6% concentrated nitric acid in 94% alcohol) etch. The time involved in each of the etching steps is dependent on the amount of surface material it is desired to remove. The amount of material to be removed is dependent, in turn, on the manner in which the specimen was manufactured. Sufficient material should be removed so that any surface stress caused in the manufacture of the specimen will be eliminated and loading stress alone will remain.

The surface of the stiffened plate in the vicinity of the weld on the side opposite the stiffener was uneven due to the variable rate of cooling of the weld. This portion of the surface was ground flat by means of a 1/4" electric

hand drill mounted with an emery disc. The grinding was done so that the camera might be more easily aimed.

A sample of the plate was used to calibrate the depth of cut obtained from the etching acids against the time of etch. The data thus obtained are given in Table II. Hand polishing following a strong acid etch of 10 minutes removes approximately 0.002".

Step (1), the drastic acid etch, leaves the surface pitted. If stress measurements were to be taken of the surface in this condition, the values obtained would be smaller than the stress actually present. The "hills" left by the pitting are unable to have stress transmitted to them due to the lack of surrounding material. It is the stress at the tops of these hills that the X-ray beam measures. Step (2), hand polishing, removes these "hills" but at the same time cold works the material. Thus, measurements taken after this step give results more compressive than the true values. Step (3), a mild etch, removes the cold work caused by the polishing. Ersoz investigations showed that this procedure resulted in stress values within the accuracy of the method.

In using this surface preparation procedure it became apparent that the process was too long and laborious to be of practical use in the field. The fundamental requirements of a surface preparation procedure are, first, that it remove a sufficient amount of material in a reasonable length of time, and second, that it leave the surface smooth, i.e.,

without "hills" and "valleys." With these requirements in mind, the possibility of using an electrolytic etch was investigated. Standard electrolytic solutions used in electro-polishing were calibrated-time against depth. The results of this calibration are also shown in Table III and Figure XVIII shows a diagrammatic sketch of the electrical circuit used. This procedure did remove the material and reduce the labor involved but did not reduce the time necessary in the preparation. Sufficient time was not available to investigate other than the standard electrolytic solutions. A combination of the acid etch and the electro-polishing was then tried on the theory that the acid etch would remove the material and the electro-polishing would remove the "hills" leaving a smooth surface. The results of the calibration of this procedure are shown in Table II. Since this technique fulfilled the requirements most satisfactorily, it was employed throughout the remainder of the investigation.

TABLE III

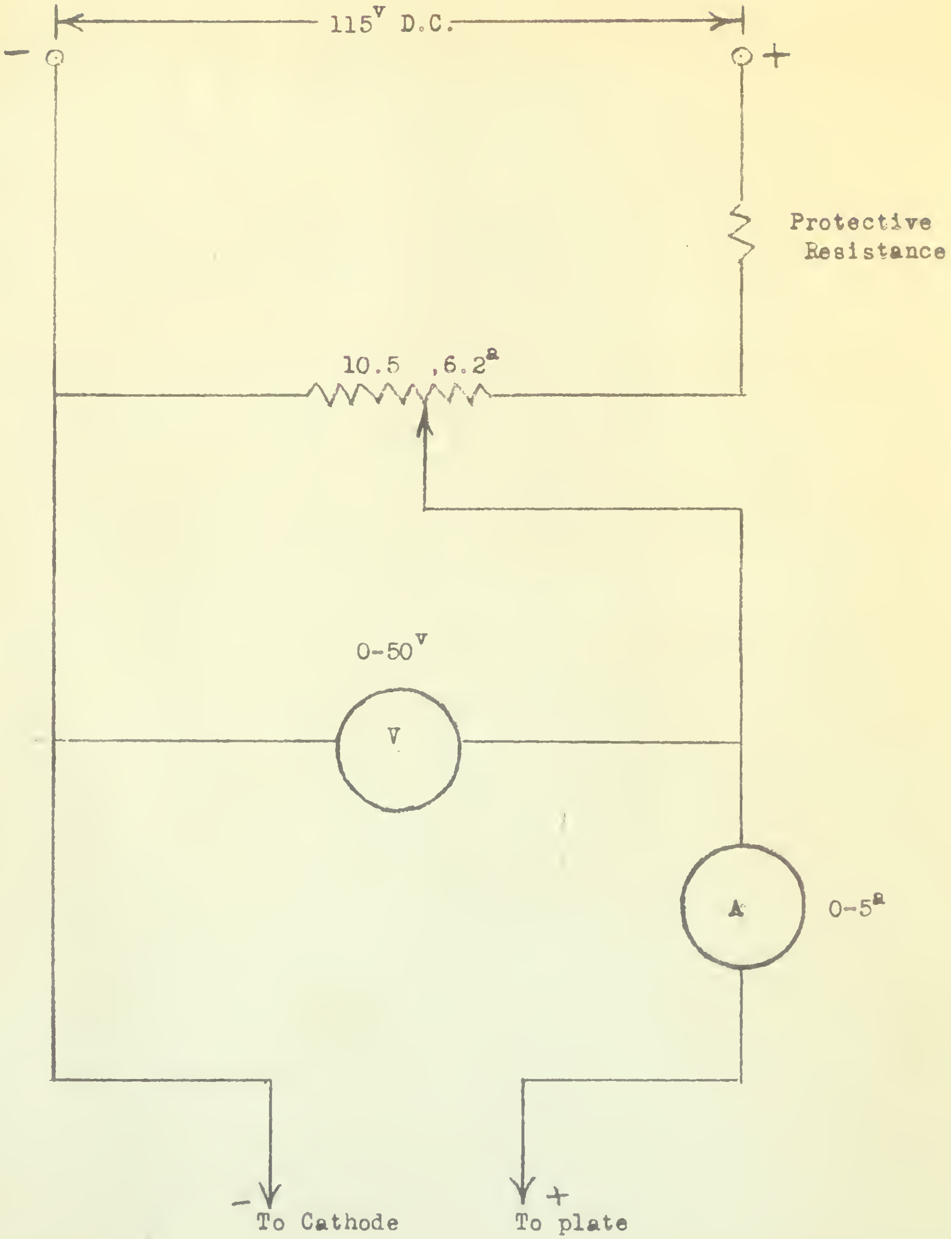
CAMERA ALIGNMENT DATA*

No.	HORIZONTAL		VERTICAL		MOVEMENT
	Left	Right	Left	Right	
1	5.98	5.74	5.97	5.96	
2	5.82	6.05	5.91	5.90	
3	5.94	5.90	5.90	5.85	O.K.
4	5.90	5.95	5.91	5.85	O.K.

* Directions are taken facing camera.

FIGURE XVIII

ETCHING CIRCUIT



As was pointed out in the Procedure, the side of the angle film closest to the specimen is used in determining Δ distance. It is this side of the film which gives the sharper lines and, therefore, results in greater precision of measurement. In addition, the evaluation of the constant, F, involved the use of the angle ψ, Figure XI. The value of ψ used was $45^\circ + \frac{a}{2}$ resulting in a constant determined specifically for the near side of the film.

SAMPLE CALCULATION

Determination of R for a tungsten ring of 50 mm. in diameter:

Cobalt radiation: $\lambda_{co}\ (K_{\alpha 1}) = 1.7889$ Angstroms

Unstressed tungsten: $a_o = 3.1647$ Angstroms

Reflecting plane: $h,k,l = 222$

$2S = 50$ mm

$S = 25$ mm.

$$d_{222} = \frac{a_o}{\sqrt{h^2+k^2+l^2}} = \frac{3.1647}{\sqrt{4+4+4}} = 0.91357$$

$$\lambda = 2\ d\ \sin\theta$$

$$\sin\theta = \frac{\lambda}{2d} = \frac{1.7889}{1.82714} = 0.979072$$

$$\theta = 78^{o}\ 15.4'$$

$$2\theta = 156^{o}\ 30.8'$$

$$\tan 2\theta = -\frac{S}{R} = -0.43509$$

$$R = -\frac{25}{0.43509} = -57.4595 \text{ mm.}$$

Determination of constant F:

$$F = -\frac{E}{2(1+V)R\ \sec^2\theta\ \tan\theta\ \sin^2\psi}$$

where

$E = 30 \times 10^6$ psi

$V = 0.28$

$R = 57.4595$

Reflecting plane = 310

$a_o(Fe) = 2.867$ Angstroms

$$d_{310} = \frac{2.867}{\sqrt{9+1+0}} = 0.90662$$

$$\sin \theta = \frac{L}{2d} = \frac{1.7889}{1.81324} = 0.986576$$

$$\theta = 80.6013^{\circ}$$

$$2\theta = 161.2026$$

$\frac{\alpha}{2}$ = correction for normal to reflecting plane

(see Figure XI)

$$= \frac{180-2\theta}{2} = 9.3987^{\circ}$$

$$\psi = 45^{\circ} + \frac{\alpha}{2} = 54.3987^{\circ}$$

$\sec 2\theta = -0.10563$

$\sec^2 2\theta = 0.0111576$

$\tan \theta = 6.041361$

$\sin \psi = 0.8130865$

$\sin^2 \psi = 0.66111$

$$F = -\frac{30 \times 10^6}{2(1.28)(0.0111576)(6.041361)(0.66111)(57.4595)}$$

$= -45,765.7$ lbs./in.^{2}/mm.

Determination of stress:

Point 1-F

	A	L
$2\theta_W = 51.71$	$2\theta_W = 51.72$	$2\theta_W = 50.50$
$\Delta'_P = 5.72$	$\Delta'_A = 5.96$	$\Delta'_L = 5.38$
corr $= -\frac{1.71}{51.71} \times 5.72 = -0.19$	corr $= -\frac{1.72}{51.72} \times 5.96 = -0.20$	corr $= -\frac{0.50}{50.50} \times 5.38 = -0.0$
$\Delta_P = 5.53$	$\Delta_A = 5.76$	$\Delta_L = 5.33$

$$s_A = -F\left[-(\Delta_p - \Delta_A)\right] = -45{,}766 \times 0.23 = -10{,}526 \text{ psi}$$

$$s_L = -F\left[-(\Delta_p - \Delta_L)\right] = +45{,}766 \times 0.20 = +\ 9{,}153 \text{ psi}$$

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